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Solutions for Ultra-High Speed Optical Wavelength Conversion and Clock Recovery

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***Abstract*— This paper reports on our recent advances in ultra-fast optical communications relying on ultra-short pulses densely stacked in ultra-high bit rate serial data signals at a single wavelength. The paper describes details in solutions for the network functionalities of wavelength conversion and clock recovery at bit rates up to 320 Gb/s.**

***Index Terms*— OTDM, clock recovery, demultiplexing, regeneration, wavelength conversion.**

I. Introduction

Despite the *post-bubble* set-back, there is still a growing pursuit of increasing the single channel bit rate, either by electronic means, reaching 100 Gb/s [1], (currently being challenged in research labs around the world) or by optical means, reaching 640 Gb/s by pure intensity modulation [2]–[5], 1.28 Tb/s using intensity modulation and polarisation multiplexing [6], and very recently 2.56 Tb/s using multilevel phase modulation and polarisation multiplexing [7].

The above achievements were demonstrated as *point-to-point* transmission experiments. The next step is to investigate how optical *networking* functionalities may be implemented at such high speeds. In that context, this paper will discuss advances in our labs as well as state the general status in the areas of all-optical wavelength conversion and regeneration at high speed as well as clock recovery.

To generate and further characterise high bit rate signals, one may employ an optical time division multiplexed (OTDM) system. A basic OTDM system is sketched in figure 1. To obtain the high bit rate, optical time interleaving is performed on pulses derived from ideally a single pulse source running at a base rate B. In a multiplexer (MUX), the original pulse train is split into N arms, corresponding to individual data channels. Each data channel may be individually data modulated (laboratory solutions often include a single modulator before the MUX), and each channel is delayed appropriately to allow for correct bit interleaving, forming a string of densely packed data pulses at the aggregate bit rate N×B. The multiplexed data is launched over a span of transmission fibre. During transmission, the signal may be impaired by group velocity dispersion (GVD), higher order dispersion, polarisation mode dispersion (PMD), non-linear effects and loss. All needs to be very carefully compensated for and some sort of passive

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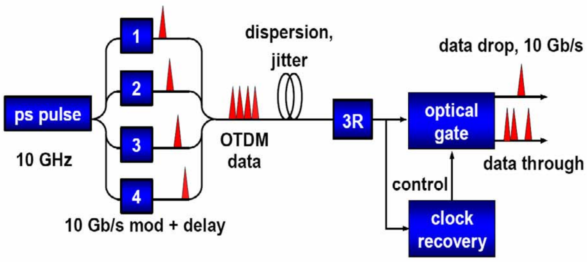

Fig. 1. A basic OTDM system. Narrow pulses are bit interleaved. Transmission impairments must be compensated for very carefully. Clock recovery with a very high timing resolution is necessary and a demultiplexer with narrow switching windows is required to demodulate the signal.

or active regeneration at the line rate may be advantageous. After transmission, at some network node, the node will need to be synchronised to the incoming data, so that it may be processed, e.g. dropping a channel (demultiplexing) in an add/drop multiplexer. The network functionalities regeneration utilising wavelength conversion and clock recovery, will be the topic of this paper. As narrow pulses form the foundation of these systems, general rules for these will also be given.

II. Pulse sources

1) Pulse requirements: Narrow high quality pulses are the essential pre-requisite for an OTDM system. The requirements to short pulse sources have been computed taking into account interference from pulse tails of neighbouring channels and the requirements to pulse tail extinction ratio (PTER) are stated in table I, where the requirement to the pulse width is that the full width half maximum (FWHM) should be 0.4× the time slot, i.e. 2.5 ps for a 160 Gb/s signal [8].

bit rate [Gb/s]	min PTER [dB]
4×40	27
8×40	33
16×40	37
32×40	41

TABLE I

Requirements to pulse tail extinction ratio (PTER) at various bit rates for a FWHM of $0.4 \times$ time slot

2) Available pulse sources: A number of different pulse sources generating narrow transform limited (TF) pulses adequate for OTDM systems have been developed and refined

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pulse source	pros	cons
ERGO PGL	TF $\sim$ 1 ps, simple, small, wavelength tuneable 320/640 Gb/s demo [9]	small rep rate tuning, trailing pulses due to AR
TMLL	TF $\sim$ 1 ps, small, tuneable λ, f, FWHM 320/640 Gb/s demo [10]	complex operation, trailing pulses due to AR
ML-FRL	TF $\sim$ 1 ps, tuneable λ in C-band 640 Gb/s demo [11]	complex architecture, bulky stability issues?
EAM [12]	TF $\sim$ 4 ps, simple, small, tuneable beyond C-band	high V_{pp}, limited to 160 Gb/s?

TABLE II

LIST OF MOST PROMISING COMMERCIALLY AVAILABLE PULSE SOURCES FOR HIGH BIT RATES. ERBIUM GLASS OSCILLATOR PULSE GENERATING LASER (ERGO-PGL), SEMICONDUCTOR TUNEABLE MODE-LOCKED LASER (TMLL), MODE-LOCKED FIBRE RING LASER (ML-FRL), ELECTROABSORPTION MODULATOR (EAM), AR: ANTI-REFLECTION COATING

within the last decade — some have reached a sufficient maturity and are now offered commercially. The most promising sources for ultra high bit rates, i.e. above 100 Gb/s are listed in table II.

3) Timing jitter: Timing jitter is a serious detrimental factor in OTDM systems. The timing jitter of a pulse train must be very low to avoid random mixing of the time channels. For 160 Gb/s data, the maximum allowed timing jitter on the data pulses is 400 fs, but for 640 Gb/s data this requirement is four times lower, i.e. about 100 fs [13]. The ML-FRL and the ERGO PGL fulfil these strict requirements. The ML-FRL, though, being a physically extended component relying on locking of many longitudinal modes, has some long term stability issues. Recently, monolithically integrated mode-locked semiconductor lasers with very low jitter have also been developed, e.g. as low as 80 fs jitter [14]. All of the mentioned pulse sources require further *pulse compression* for use at 640 Gb/s, see e.g. [5].

4) Dispersion requirements: Table III shows the tolerances to dispersion (D) and dispersion slope (S) in terms of how much residual D and S can be tolerated before a power penalty of 1 dB is suffered during transmission. The table also lists how many metres of standard single mode fibre (SMF) these values correspond to.

	D [ps/nm]	S [ps/nm^2]	SMF [m]
160 Gb/s	2	5	100
640 Gb/s	0.13	0.07	7

TABLE III

DISPERSION TOLERANCES AT 160 AND 640 GB/S

Dispersion compensating fibre (DCF) is widely used, but phase modulation has recently been introduced to provide for fine tuning of the dispersion compensation, e.g. compensation of third order dispersion [6], [15], and for pre-compensation [16], [17] or even post-compensation [18].

III. CLOCK RECOVERY

After transmitting the data, one will need to synchronise a gate to it before processing it. This is increasingly challenging at high bit rates, since an OTDM signal no longer contains a frequency component at the base rate, and so far locking to data rates above 160 Gb/s has only been achieved by a few groups worldwide [19]–[21]. In all cases, phase-locked loops (PLL) using phase mixers with very high timing resolution were used. Table IV contains a short list of the current status on bit rate limits for various mixer types.

mixer	bit rate
electrical	100 Gb/s [22]
electro-optical, e.g. EAM	160 Gb/s [23], [24] (320 Gb/s DPSK [19])
all-optical, e.g. FWM-SOA	400 Gb/s [20]

TABLE IV

SUMMARY OF CURRENT BIT RATE LIMITS FOR VARIOUS MIXERS IN PLL-BASED CLOCK RECOVERY SCHEMES

An all-optical approach is the only alternative when going to very high bit rates (beyond 160 Gb/s). At these rates one can utilise extremely fast non-linear all-optical effects such as four wave mixing (FWM) or cross-phase modulation in SOA-based devices.

5) FWM-based clock recovery: Figure 2 shows the set-up of a FWM-based clock recovery scheme for 160 Gb/s operation.

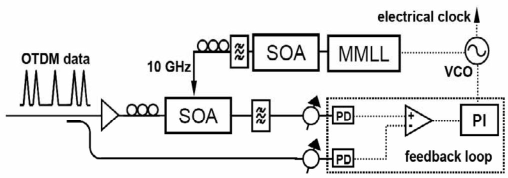

Fig. 2. FWM-based clock recovery set-up.

The set-up contains three active semiconductor components: a monolithic mode-locked laser (MMLL), an amplifying SOA and an SOA for FWM. All these active components are InGaAsP multiple quantum well (MQW) devices and may be integrated on one chip. The heart of the set-up is the phase comparator SOA (PC-SOA: 2 mm long, 8 quantum wells (QWs) for efficient FWM). Instead of an EDFA in the loop [20], a considerable improvement is found by shortening the loop using a booster SOA (2 mm long, 3 QWs ensuring high saturation output power). The MMLL is an all-active 2 QW laser, ensuring narrow pulses (3.9 ps) and low timing jitter (τ_{jitt}~80 fs), running at 10 GHz at 1560 nm [25]. The OTDM data is amplified, merged with the clock pulses and injected

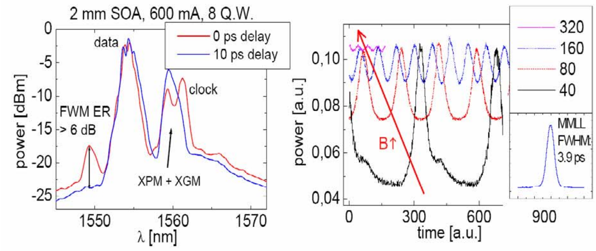

Fig. 3. FWM-based error signals. Left: spectrum with no control-data pulse overlap (10 ps delay) and with overlap (0 ps delay) resulting in FWM. Right: error signals at bit rates from 40-320 Gb/s.

into the PC-SOA to generate FWM. Filtering out the FWM wavelength yields an error signal proportional to the phase difference between the data and the clock pulses. The error signal is leveled to zero by balancing the two photodiodes (PD, 100 MHz bandwidth), thus generating a bipolar signal. This is fed back, through a proportional integrator filter (PI), to a voltage controlled oscillator (VCO), which drives the MMLL.

Figure 3 shows the error signals produced with the FWM-based scheme. The timing resolution is determined by the clock pulse (3.9 ps), which can clearly resolve the individual data pulses for bit rates from 40-160 Gb/s.

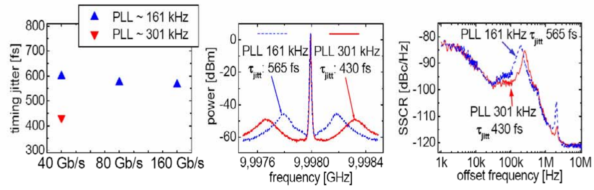

Fig. 4. FWM-based results. Left: Jitter of the recovered clock at various bit rates. Middle: microwave spectrum of recovered clock. Right: SSCR. Optimisation of the PLL-bandwidth reduces the sideband noise, thus lowering the jitter.

The locking performance is characterised by the timing jitter of the recovered clock, measured with the single sideband to carrier ratio (SSCR) method [26], and becomes about 600 fs. Figure 4 (left) summarises the measured jitter values at the various bit rates: the jitter is basically independent of the incoming bit rate, remaining just less than 600 fs for a PI-bandwidth of 161 kHz. The loop length is 22 m due to various pigtails, corresponding to a delay of about 110 ns. The PI-filter needs to be slower than the delay in order to actively track the data signal, and for a 110 ns delay the bandwidth must be less than 350 kHz to obtain a lock, as theoretically predicted in [27]. Thus, lower timing jitter may be obtained by shortening the loop and increasing the bandwidth.

Figure 4 (middle and right) show the microwave spectrum and the SSCR measurements when the PI-bandwidth is experimentally optimised to the upper limit 301 kHz. The sideband phase noise peak at 190 kHz is clearly suppressed and pushed out to 270 kHz, corresponding to a timing jitter reduction of more than 100 fs. The optimised jitter (430 fs) would be adequate for error free demultiplexing of the 160 Gb/s data signal [13]. The jitter may be reduced further by shortening the loop [24] by integration of the compact semiconductor components.

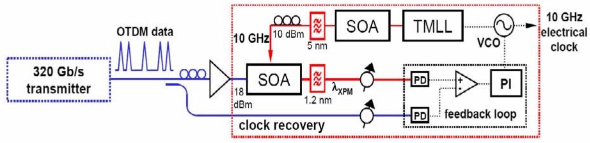

Fig. 5. Set-up for f-a XPM-based CR.

6) 320 Gb/s Filtering-assisted XPM-based clock recovery: A pulsed control laser with narrower pulses is introduced and filtering-assisted cross-phase modulation (f-a XPM) in an SOA enables locking to 320 Gb/s. Again, all active components are semiconductor-based.

Figure 5 shows the set-up for locking to 320 Gb/s. The data signal, based on 1.3 ps pulses at 1555 nm, is amplified and spectrally filtered before injected into the clock recovery circuit together with the local SOA-boosted clock signal, a 10 GHz pulse train from a commercial semiconductor tuneable mode-locked laser (TMLL) driven by the VCO. The used SOAs are the same as in the FWM case. The TMLL is running at 1560 nm with a pulse width of 2.2 ps. Here, filtering-assisted cross-phase modulation of the clock pulses by the data pulses is used as mixing process. As the data pulses travel through the SOA, they give rise to changes in the carrier density due to ultra-fast carrier dynamics such as spectral hole burning (SHB) due to stimulated emission, carrier-carrier scattering (C-C) and carrier heating (C-H). This results in a phase modulation of the clock pulses, i.e. they get chirped. This chirp may be used to enhance the speed response of an SOA if a narrow filter is placed at the SOA output [28]. In this experiment, a 1.2 nm filter is centred on the red shifted side of the clock $\sim$1562 nm. A phase modulation of the clock is thus transferred into an intensity modulation, which can be directly detected, generating an error signal.

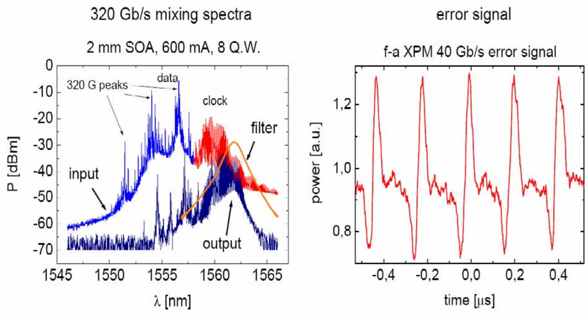

Fig. 6. Error signals by f-a XPM. Left: SOA input and filtered output spectra. Right: Generated error signal for a 40 Gb/s data signal.

Figure 6 shows the input and filtered output spectra from the SOA together with a 40 Gb/s error signal. The filter is tuned so that both an amplitude and phase change are allowed through, yielding a dispersion shaped 3-level curve [28].

Figure 7 shows error signals for 80, 160 and 320 Gb/s together with the locking results. In all cases, it is possible to obtain locking and with similar performance, again demonstrating that the speed limitation mostly stems from the mixer. The best locking performance obtained for this set-up

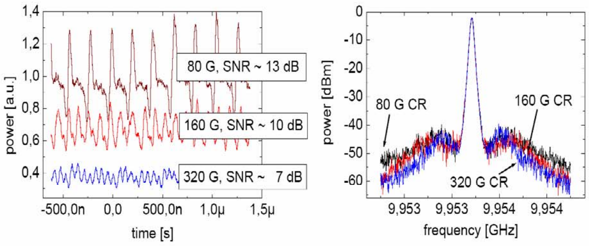

Fig. 7. Error signals by f-a XPM up to 320 Gb/s (left) and microwave power spectra of the locked clock up to 320 Gb/s.

corresponds to a timing jitter of 800 fs, which is due to PLL-noise from the VCO, the TMLL (400 fs jitter on its own), the mixer, and the active components in the loop filter. This jitter value can be further reduced by minimising these noise sources and further reduce the length of the loop, and use narrower clock pulses.

IV. Wavelength conversion and regeneration

160 Gb/s regeneration [29] and wavelength conversion [30]–[36] have only been demonstrated by a few groups worldwide so far. In this section, a fibre-based Raman-assisted 160 Gb/s (and above) regenerative wavelength converter is described.

7) 160 Gb/s wavelength conversion and regeneration: A wavelength converter based on notch-filtered cross-phase modulation (XPM) assisted by Raman gain is shown in Figure 8.

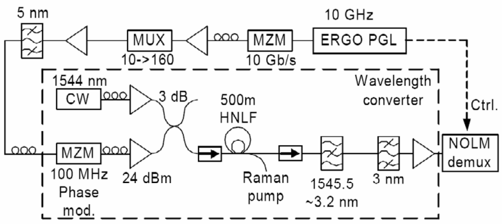

Fig. 8. Raman-assisted XPM regenerative wavelength converter.

The optical signal is generated by an ERGO-PGL at 10 GHz and 1557 nm. Data modulation and multiplexing to 160 Gb/s are done as previously described with a multiplexer. Phase modulation is performed by a symmetrically driven MZM at 100 MHz to suppress Stimulated Brillouin Scattering (SBS) from the narrow spectral components of the multiplexed high speed signal [37]. The signal is amplified by an EDFA to 24 dBm and combined with a 14.6 dBm CW at 1544 nm and $\sim$500 MHz line-width before injection into 500 m of highly non-linear fibre (HNLF), with a zero dispersion at 1551 nm, a dispersion slope of 0.017 ps/nm^{2}km, and a non-linear coefficient $\gamma \sim$10.5 W^{-1}km^{-1}. In the HNLF a counter-propagating 200 mW Raman pump enhances the XPM process and provides amplification of the signal. The data generates sidebands on the CW carrier through XPM mediated by the Kerr effect in the HNLF. As sidebands on either side of the carrier are out of phase it is imperative to select only one sideband [33]. This is done using a custom made Fibre Bragg Grating (FBG) as a notch filter to suppress the CW and one XPM sideband and a band pass filter to suppress the original data signal. The FBG has its centre wavelength at 1545.5 nm and a bandwidth of 3.2 nm. The wavelength converted signal is demultiplexed in a non-linear optical loop mirror (NOLM) to the 10 Gb/s base rate using 2 ps control pulses from the 10 GHz 1557 nm pulse source.

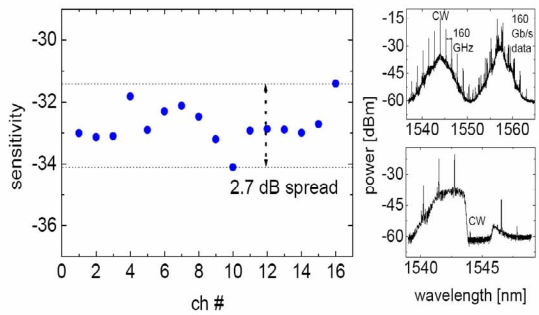

Fig. 9. Raman-assisted XPM regenerative wavelength conversion. Left: receiver sensitivities of all converted and demultiplexed channels. Right: output spectrum of HNLF (top) and after notch and band pass filtering (bottom).

BER measurements are performed to evaluate the system performance and the receiver sensitivity (BER 1E-9) results for all channels are shown in figure 9. Figure 9 (top, right) shows the data signal spectrum and the XPM broadening of the CW spectrum recorded at the output of the HNLF before filtering. Strong 160 GHz modulation peaks can be seen in the XPM broadened spectrum indicating a significant stabilisation of the phase in the converted signal compared to the input signal, owing to the high coherence of the CW source [38]. Figure 9 (bottom, right) shows the spectrum of the converted signal after filtering. The CW and part of the red sideband are suppressed $>$ 40 dB and the strong 160 GHz spectral components are retained after filtering.

All channels are error free with an average sensitivity of -33 dBm with a variation of 2.7 dB, resulting in an average penalty of 0.4 dB compared to the 10 Gb/s back-to-back. The 2.7 dB spread is due to amplitude variations in the multiplexed signal. The fact that one channel is clearly better than the original 10 Gb/s signal indicates that there are regenerative properties of the process, and indeed the zero level in the converted signal is generally suppressed with respect to the incoming signal [34].

8) 160 Gb/s transmission and in-line wavelength conversion: The Raman-assisted wavelength converter is placed in an in-line transmission link to verify its transmission capability [36]. The set-up used is depicted in figure 10. In this particular set-up, a 10 GHz pulsed clock signal is transmitted with the data signal but in orthogonal polarisation. Thus the clock and data can be on the same wavelength — this reduces the amount of needed pulsed laser sources to one.

After transmission through 80 km SMF and appropriate DCF for GVD/slope compensation, the signal is converted to 1543 nm, and subsequently transmitted through a 50 km span of SMF-IDF, before being demultiplexed in a NOLM using the 10 GHz transmitted clock pulses as control.

Figure 11 (left) shows the receiver sensitivities of all 16

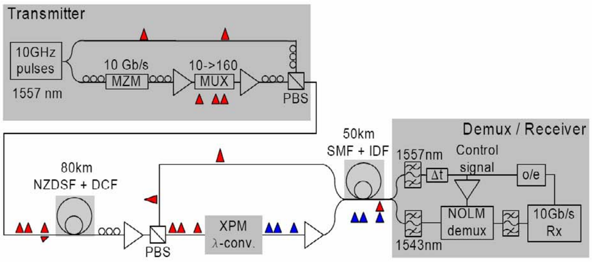

Fig. 10. In-line 160 Gb/s wavelength conversion set-up.

demultiplexed converted data channels after the first 80 km transmission span. All channels are error free with a spread of about 3 dB in sensitivity. The channels closest to the transmitted clock pulse suffer from a slightly larger penalty due to incomplete polarisation extinction. Figure 11 (right) shows an oscilloscope trace of the detected clock signal (in a 14 GHz detector, which broadens the pulse to a sine), and the 160 Gb/s eye detected on a 50 GHz detector and a 70 GHz scope, which indicates a clear 160 Gb/s structure. The clock signal is a clear well-defined trace with low timing jitter (~ 300 fs), sufficient for stable demultiplexing.

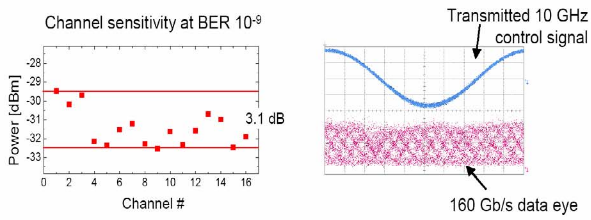

Fig. 11. 80 km SMF followed by 160 Gb/s wavelength conversion. Left: Sensitivities of all 16 demultiplexed channels. Right: Transmitted detected clock signal and 160 Gb/s converted eye (on 70 GHz scope).

Figure 12 (left) shows the results for all 16 channels in terms of receiver sensitivities after the full 130 km transmission and conversion. All 16 channels show good performance, however, after the final transmission stage the channel coinciding with the clock pulse is influenced by the clock pulse too much to get error free performance (1.1E-8 BER obtained). Again, this is because of the incomplete polarisation extinction in the first span, which is accumulated through the last span. The remaining 15 channels are all error free with a sensitivity spread of about 4.5 dB. Also shown are the results for the case when no Raman pump is used, which increases the penalty with 0.8 dB.

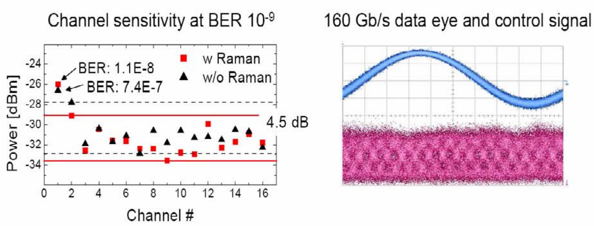

Fig. 12. In-line 160 Gb/s wavelength conversion after full 130 km transmission. Left: Sensitivities of all 16 demultiplexed channels. Right: Transmitted detected clock signal and 160 Gb/s converted eye (on 70 GHz scope).

Figure 12 (right) shows the detected clock signal and additional timing jitter is observed on the clock (~ 450 fs). So, the clock signal has clearly deteriorated through the last span, but the majority of channels still retain an average sensitivity of about -32 dBm, as before the last span. It is only the channel overlapping with the clock that is completely distorted, so there may be some spectral mixing between the clock pulse and the coinciding data pulse.

To summarise, this final section has shown that the wavelength conversion concept described here relying on Raman-assisted cross-phase modulation truly works in a real transmission link. Furthermore, it should be mentioned that this technique is scalable to higher bit rates, and it has recently been demonstrated at 320 Gb/s [39].

V. Conclusion

This paper has described some recent advances within the fields of ultra-fast clock recovery and all-optical wavelength conversion. We have described how various laboratory solutions for clock recovery for operation at 160 Gb/s and 320 Gb/s have been developed and experimentally verified, relying only on compact semiconductor components. It was found that filtering-assisted cross-phase modulation could be used as an ultra-fast all-optical *mixer* in a PLL-based clock recovery scheme operating up to 320 Gb/s. The fact that the whole circuit was based on compact semiconductor devices, indicates that this may be a viable solution for future monolithic integration into a single cheap component with a small footprint. We furthermore showed results on 160 Gb/s wavelength conversion utilising benefits of Raman gain in non-linear fibres. The scheme was tested in a back-to-back situation as well as in a transmission link showing error free performance.

All in all, we have demonstrated that there are solutions for chosen key functionalities pertaining to high speed operation of optical networks, reaching 160 and 320 Gb/s. There are many impressive results in the literature, and with the ones mentioned here, the future of high speed communications looks bright.

Acknowledgments

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